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The subjective effects of interchannel phase-shifts on the stereophonic image localisation of wideband audio signals

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THE SUBJECTIVE EFFECTS OF INTERCHANNEL PHASE-SHIFTS ON THE STEREOPHONIC IMAGE LOCALISATION OF WIDEBAND AUDIO SIGNALS

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Summary

This report describes a series of subjective tests concerned with the effects of interchannel phase-shifts on stereophonic image localisation. The tests, involving listeners experienced in subjective auditory judgements, were carried out in both a free-field room and a listening room.

Quantitative information is given on the effects of phase-shifted signals on image position and spread. In addition, subjective data is given on the acceptability of such signals in programme material. The results are of relevance to the stereo compatibility of matrix quadraphonic systems. In addition, they may prove useful in producing novel spatial effects for use in normal stereophony.

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1. Introduction

1.1. The broadcasting aspects of quadraphony

Various techniques for increasing the flexibility and realism of reproduced sound are at present being investigated. Stereophonic reproduction, involving two loudspeakers, conveys a degree of spatial information which is lacking in monophonic presentation. Quadraphonic systems, using four loudspeakers arranged around the listener, attempt to give further spatial improvements; with these, it is hoped to be able to create a more realistic reverberant sound field for classical music, or to exploit various effects only possible when the listener can, in effect, be surrounded by instruments.

This is not the place to discuss the various quadraphonic systems at length, since much has been written elsewhere.[1,2,3,4,5,6] It is necessary, however, to distinguish between two main approaches to quadraphonic sound. These are the discrete and matrix systems. In discrete systems, the four source signals or four linear combinations of them are retained intact throughout all signal processing. On the other hand, matrix systems attempt to reduce the number of transmission channels, by means of a coding method that exploits the hitherto unused parameter of phase. In such systems, the four original source signals are reduced to two by the application of a suitable phase and amplitude matrix. The two signals thus derived contain relative-phase as well as amplitude information, and this phase content can be used in an attempt to reconstruct directional information from the original source signals. Thus, for quadraphonic reproduction, a suitable phase and amplitude decoding matrix is applied to the two derived signals, to reproduce four signals simulating the original quadraphonic sound field.

From the point of view of information theory, a perfect reconstruction of the original information is impossible, and unwanted phase-shifted crosstalk in the reproduced channels is the major impairment resulting from this encode/decode process. This crosstalk is not present in discrete systems, which never intentionally introduce phase shifts into the signals; as a result, these are, in principle, capable of better quadraphonic reproduction than matrix systems. The improved performance is, however, obtained by the use of more complex equipment than that necessary for basic matrix systems. For instance, the application of discrete methods to disc-reproduction involves both cutting difficulties for the manufacturer and groove-tracking problems for the user. Similarly, proposed discrete broadcasting systems encounter difficulties because of their increased susceptability to noise and interference.[14,15]

At the moment, proponents of both discrete and matrix systems are concentrating their efforts on disc-recording. However, the feasibility of broadcasting the respective systems are being considered. In this respect, the matrix methods have a distinct advantage: with the addition of only a relatively simple encoder, two signals derived by matrixing can, in principle, be transmitted using existing stereophonic equipment. On the other hand, discrete four-channel broadcasts may require an increase in the number of frequency allocations, necessary, to avoid problems of co-channel and adjacent channel interference, if area coverage is to be maintained. In addition, such broadcasts would certainly require extensive changes in signal-distribution facilities.

Yet another factor to consider is stereo compatibility. With matrix quadraphony, a stereophonic receiver or disc player interprets the two matrix-derived signals as the usual left and right stereo signals. Since the operation of the encoding matrix introduces interchannel phase-shifts which may be disturbing in stereo presentation, compatibility is not assured. As listeners to quadraphony are expected to be in the minority for many years to come, this could be a serious problem. Investigations have therefore been made into the subjective effects of such phase-shifts on programme material presented stereophonically, and these results can be used to aid assessment of the stereo compatibility of matrix quadraphonic sound systems.

The work is described in two reports; the first (and present report) deals with image localisation using wideband phase-shifted audio signals. A second report[12] deals with narrowband signals, in an attempt to investigate certain frequency-dependent localisation effects. It should be stressed that both reports deal implicitly with stereophonic programme presentation only. Work on subjective localisation in quadraphonic presentation has been reported elsewhere;[7,8] however, it is felt that the results obtained in the present reports are also likely to prove useful in investigations into quadraphonic sound reproduction.

1.2. The stereo presentation of matrixed quadraphonic information

The two primary variables affecting stereophonic image properties are the interchannel level-difference and the interchannel phase-difference; however the quality of the loudspeakers used and the acoustics of the listening environment can also affect image localisation. In conventional stereophony phase is not normally exploited, and a sharp image can be obtained for a point sound-source by feeding in-phase signal components to the two loudspeakers; assuming symmetry in the listening environment, the position of the resulting image will be dependent only upon the interchannel level-difference.[9,10,11] However, in the stereophonic presentation of two matrixed-quadraphonic signals, the components in each channel may differ in phase. In this case, the position and width of the resulting stereophonic image depends on both interchannel level and phase-differences. Furthermore, it is often found that such images, as well as being diffuse, are spatially displaced with respect to in-phase images. In the limit, antiphase signals may, under certain conditions, cause the image to become completely diffuse and unlocateable. Such images often seem to come from 'inside the head', and are usually considered to be highly objectionable.

A further parameter called the 'subjective disturbance factor' is found to be useful in assessing this sort of effect. This factor attempts to provide a quantitative estimate of the degree of discomfort experienced by listeners, when presented with signals characterised by large interchannel phase-shifts. Another effect, the elevation of an image above the plane of the loudspeakers, is not considered here: this phenomenon usually only becomes important when the angle subtended by the loudspeakers at the listener exceeds the normal 60°.

The situation may be summarised as follows:

1. A sound image may be characterised by three parameters, which may be inter-dependent.
   (a) Position with respect to the loudspeakers.
   (b) Spread.
   (c) Subjective disturbance factor.
2. The variables affecting these image parameters are:
   (a) Interchannel level-difference.
   (b) Interchannel phase-difference.
   (c) Acoustics of the listening environment.
   (d) Performance (quality) of the loudspeakers used.

The next section will deal with the experimental details involved in investigating the effects of the first three variables on stereophonic image localisation.

2. Experimental procedure

Much work has already been done on the relationship between interchannel level-difference and image position for in-phase stereophonic signals.[9,10,11] Clearly, in the investigations described here, the significant new variable is the interchannel phase-difference. Tests were therefore carried out with a few carefully selected interchannel level-differences, but with a relatively wide range of phase-differences. The format chosen for the tests was a series of A/B comparisons. The two sound images compared in each test were produced by:

(A) in-phase signals with a known interchannel level-difference, and

(B) signals with a known phase-difference, and the same level-difference as in (A).

(The phase-difference was nominally independent of frequency.*)

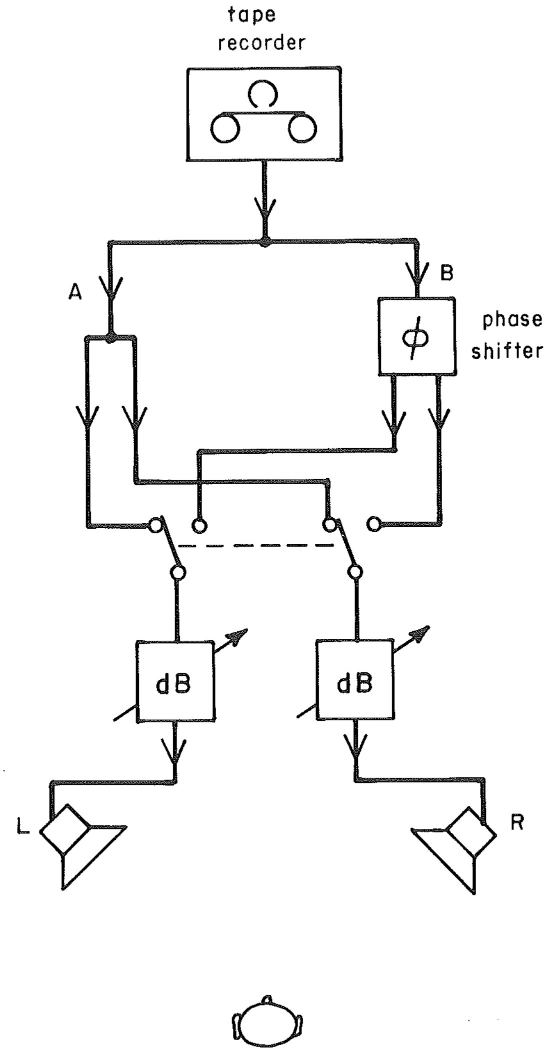

Fig. 1 - Schematic representation of experimental arrangement

Fig. 1 shows, in schematic form, the equipment used to generate these two conditions. A high-quality tape recorder replayed a tape containing a continuously repeated excerpt of male speech (the spectrum of the material is indicated in Fig. 2), and this monophonic signal was fed into circuits A and B. Circuit A provided two equal in-phase signals which, when fed through a pair of channel

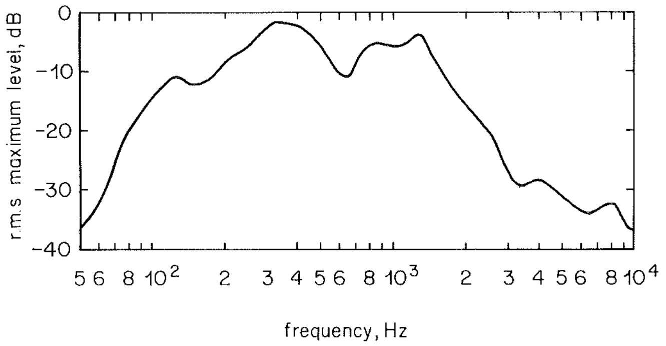

Fig. 2 - Spectral content of male voice programme material used in subjective tests

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* See Appendix II.

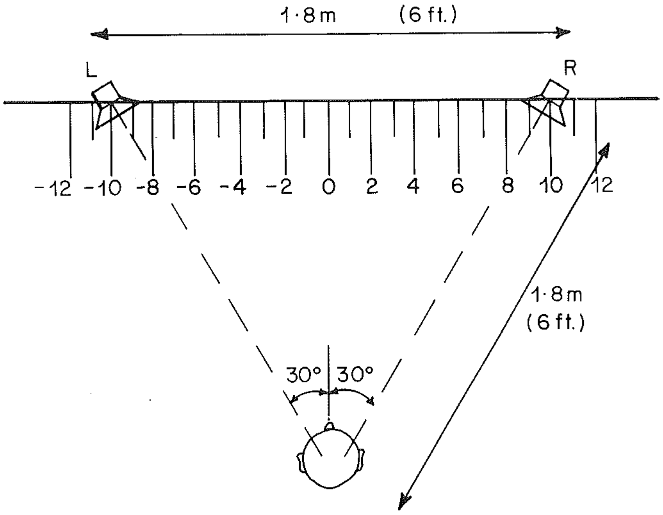

Fig. 3 - The experimental layout

attenuators and loudspeakers, gave the reference sound image (A). Circuit B, incorporating a phase-shift network,* gave two equal-amplitude signals having the required phase-difference; these signals were then used to provide the test image (B). The signals from circuits A or B could be selected by a switch controlled by the listener. A further switch, controlled by the tester but concealed from the listener, randomly reversed the action of the listener's switch between tests, so that he could never know from past experience which of his switch positions selected the co-phased or non co-phased signals.

The loudspeaker arrangement is shown in Fig. 3. An accurately measured equilateral triangle, of side 1·8 m (6 ft), was marked on the floor. Two closely matched monitoring loudspeakers were positioned on the base points of the triangle, with a numbered scale hanging above them. In addition a vertical length of tape was suspended 0·9 m (3 ft) behind the loudspeakers and accurately centred between them. The listener sat at the vertex of the triangle, with his head held roughly central by a head-rest. A very precise alignment of the head could then be ensured by asking the listener to satisfy himself that the parallax shift between this tape and the centre of the scale was symmetrical with respect to both eyes. This exact head alignment was felt to be necessary since previous work had indicated that absolute stereophonic image localisation was dependent on the precise position of the head.[10] It is considered that the results obtained should be relevant to any nominally central listening position, though only the general conclusions are expected to apply for markedly off-centre positions.

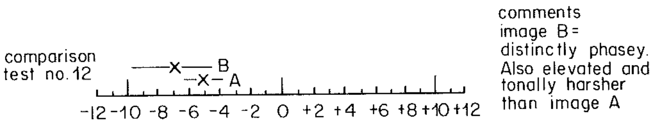
comparison test no. 12
B
A
-12 -10 -8 -6 -4 -2 0 +2 +4 +6 +8 +10 +12
comments
image B = distinctly phasey. Also elevated and tonally harsher than image A

Fig. 4 - The format of listener results sheets

Each listener taking part in the tests was provided with a duplicated results sheet, and a written list of instructions with which he was asked to familiarise himself. The results sheet was graphic in form, with the scale marked from −12 to +12 for each comparison test, to correspond with the scale above the loudspeakers. The listener was asked to mark the position of both the A and B images by crosses, and to indicate the image widths by lines centred on these crosses. He was also asked to comment if he found any image exhibited a phasey quality and to indicate any other feature of the images thought to be noteworthy. Thus, the result of a single typical comparison test for a given listener might appear as in Fig. 4.

The tests were performed in a free-field room and then repeated in a listening room. The free-field room, although an unrealistic listening environment, gives conditions which are reproducible by other investigators. Another reason for using this environment was that it was expected that the subjective effects of the non co-phased signals would be emphasised more than in a listening room, where they might be masked by the reverberant sound-field. The free-field room has a surface reflection of less than 10% at all frequencies above 40 Hz, and the listening room, 6·2 m (20·5 ft) x 3·8 m (12·5 ft) x 3 m (10 ft) high, has a reverberation time of 0·35 seconds.

It was not found practicable to use acoustically transparent curtains in the free-field room to hide the loudspeakers from the listener and so, for consistency, no curtains were used in the listening room. Previous work has indicated that visual cues do not affect the auditory judgements of trained observers.[10] This was confirmed in these experiments.

Five observers, all experienced in subjective acoustic work, took part in the tests. It will be recalled that each test consisted of a comparison between (A) a reference sound-image characterised by an interchannel level-difference D_L, but with both channels co-phased, and (B) a test image provided by the same value of D_L, but with a wideband interchannel phase-difference, D_P.

Four interchannel level-difference figures were used:

1. D_L = 0 dB : L = −6 dB, R = −6 dB* – giving a central image for co-phased signals;
2. D_L = 4 dB : L = −8 dB, R = −4 dB) L = −4 dB, R = −8 dB) – giving noticeably off-centre images;
3. D_L = 8 dB : L = −12 dB, R = −4 dB) L = −4 dB, R = −12 dB) – giving images roughly equidistant between a loudspeaker and the centre;
4. D_L = 14 dB : L = −16 dB, R = −2 dB) L = −2 dB, R = −16 dB) – giving images just offset from each loudspeaker.

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* See Appendix II.

* L = level of left loudspeaker with respect to an arbitrary zero level.
R = level of right loudspeaker with respect to the same zero level.

All images thus formed were of approximately equal intensity: a level of 76 dBA at the listening position, measured with a sound-level meter, was used in both environments. The interchannel phase-difference figures were:

In the free-field room; $D_P = 0°, \pm6°, \pm11°, \pm22°, \pm45°, \pm67°, \pm90°, \pm135°, \pm180°$

In the listening room; $D_P = 0°, \pm22°, \pm34°, \pm67°, \pm90°, \pm135°, \pm180°$.

Each listener was allowed as much time as he thought necessary for the tests; on average this was about a minute per comparison and, to avoid fatigue, everyone completed his large quota of tests in a number of sittings.

3. Interpretation of results

The complete numerical results may be found in Tables 2–5 of the Appendix. Each table gives the results corresponding to one value of interchannel level-difference, D_L. It quickly became apparent that all results showed left/right symmetry, and therefore, in order to simplify the presentation of the results, all data has been normalised, and only images for right-dominant signal-levels are considered. All the image-position figures refer to the scale, illustrated in Fig. 3, in which the loudspeakers are situated at the ±10 units positions.

It will be recalled that listeners were asked to estimate the positions of the reference and test images by means of a direct A/B comparison. Because of the format of these tests, it is hardly surprising that the most consistent results were obtained for estimates of the difference in position of the reference and test images, rather than for the absolute position of each image. The following figures illustrate this well:

1. standard deviation of estimated position for reference image = 0·9 units;
2. standard deviation of estimated position for test image = 1·25 units;
3. standard deviation of estimated position-shift between the two images = 0·8 units.

(A more complete list of standard deviations may be found in Table 6 of the Appendix.) Because of the relative consistencies of these estimates, the positions of test images in Tables 2–5 were obtained by adding the mean estimated position-shift to the mean estimated reference-image position.

The image-spread figures given in the tables refer to the angle subtended at the listener by the test images. The subjective degree of phasiness gives a measure of the disturbance factor for these images. This is expressed on the scale:

0 = 'not phasey'
1 = 'just detectably phasey'
2 = 'distinctly phasey'
3 = 'objectionably phasey'

Graphical representations of the experimental results are shown in Figs. 5 to 10. Figs. 5 to 8 are graphs of image position versus interchannel phase-difference, for a given channel level-difference. The position of each image is marked by a small circle, and the length of the line through that circle indicates the image-width; the figure next to the line gives the subjective disturbance factor for that image. Figs. 9 and 10 are graphs of image position versus interchannel level-difference, for given phase-differences. These figures are discussed in the next section.

4. Discussion of results

Figs. 5–10 show quite unmistakeable and consistent trends. Some of these trends agree with intuitive judgements, while others are rather unexpected.

Comparing the curves marked (i) and (ii) in each of the Figs. 5 to 8 it is possible to see the differences between the results obtained in the free-field and normal listening environments.

The fact that subjective disturbance factors are consistently higher in the free-field room shows that it is much easier to detect phasey effects in this environment. The differences in positional displacements and image spreads are not very marked, but in general, both of these factors are slightly larger in the free-field room.

In Figs. 5–8 it can be seen that the effects of interchannel phase-difference depend to a large extent on the interchannel level-difference. As this increases, a given interchannel phase-difference causes decreasing image shifts and spreads, and less subjective disturbance. Thus it is difficult to produce images very far outside the loudspeakers but such images, if produced, tend not to be objectionably diffuse or phasey.

A rather unexpected phenomenon is observed when the effects of phase-leading and lagging signals are examined. In Fig. 5, which applies to central images with zero interchannel level-difference, the image displacements are symmetrical with respect to the sign of the channel phase-difference; images shift towards the phase-leading loudspeaker, and this displacement, together with the image spread, is nominally proportional to the magnitude of phase-difference. This phenomenon of images shifting towards a phase-leading (and hence time-leading) source is merely an example of the Haas Effect.[9] However, symmetry with respect to the sign of the phase-difference is not maintained in Fig. 6 where the level-difference is 4 dB. In this case, the displacement towards the phase-leading loudspeaker is far greater when this source is the louder of the stereo pair. The images produced when the quieter loudspeaker leads are not significantly displaced, but are diffuse and subjectively disturbing.

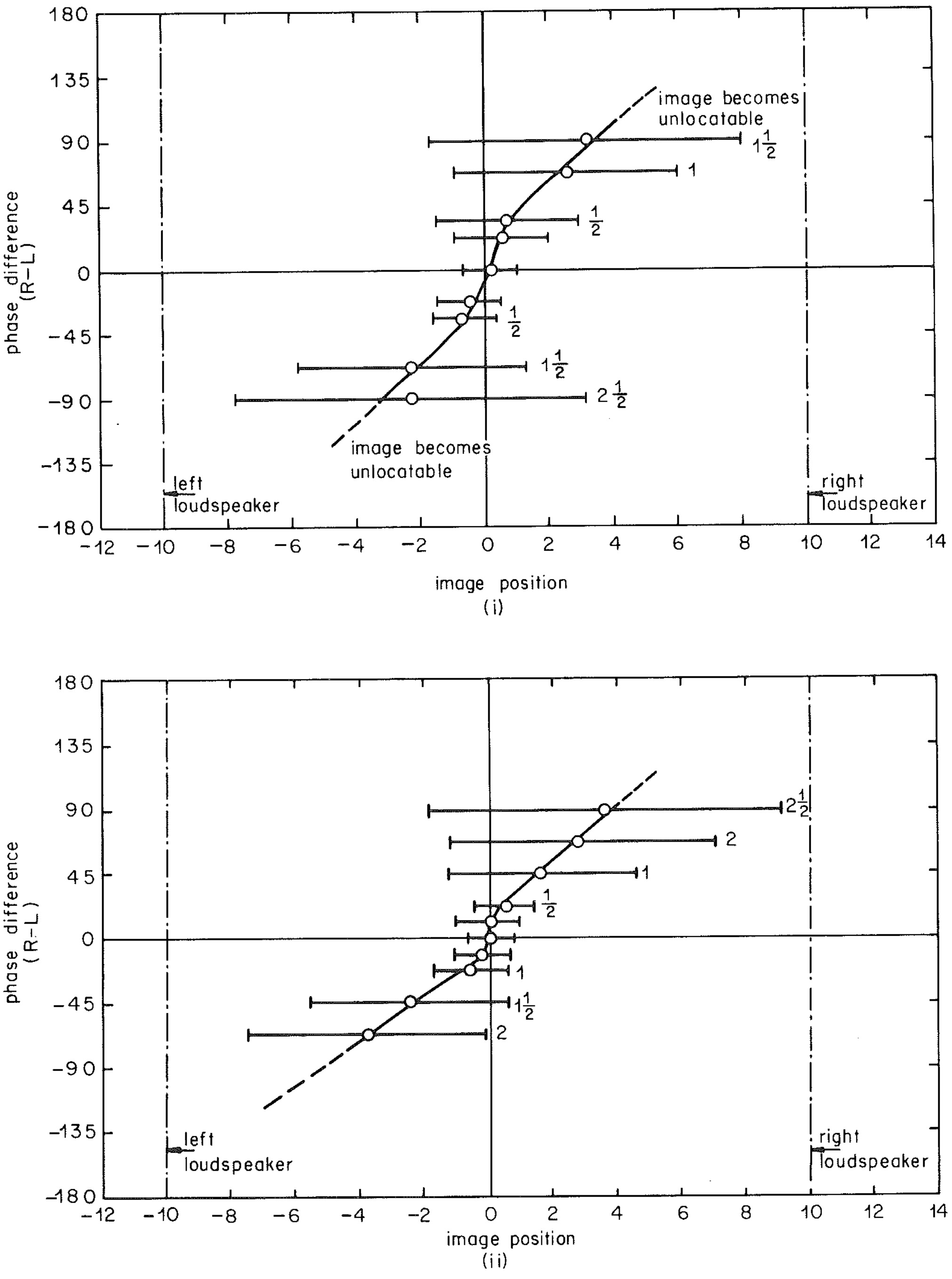


Fig. 5 - Image position versus interchannel phase-difference, for an interchannel level-difference of 0 dB

├——O——┤ N

Experimental result showing

image position .... O

image width .... ├——┤

and subjective disturbance factor... N

N	Image Quality
0	not phasey
1	just detectably phasey
2	distinctly phasey
3	objectionably phasey

(i) in listening room (ii) in free-field room

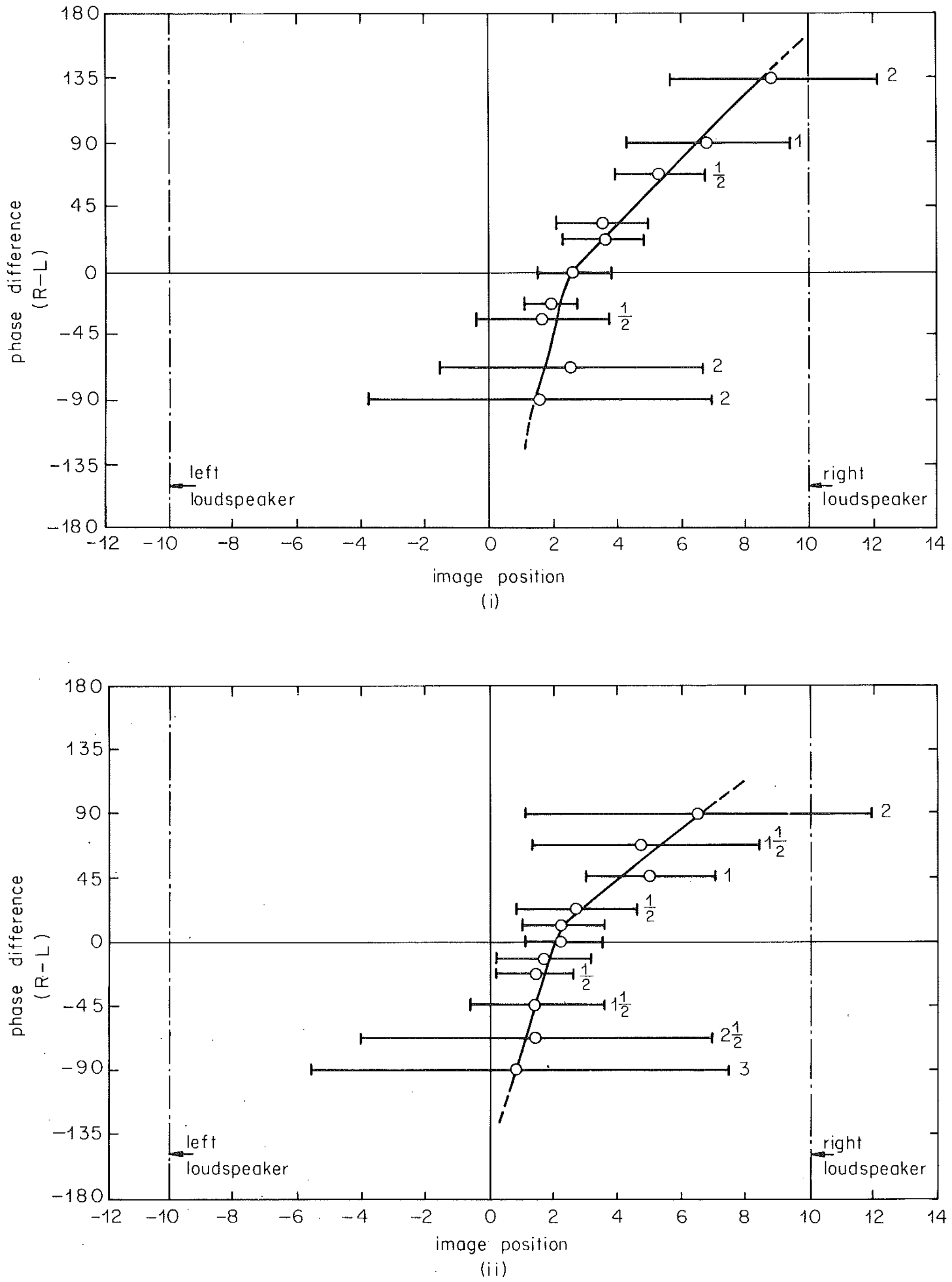


Fig. 6 - Image position versus interchannel phase-difference, for an interchannel level-difference of 4 dB

├──O──┤ N

Experimental result showing

image position .... O

image width .... ├──┤

and subjective disturbance factor... N

N	Image Quality
0	not phasey
1	just detectably phasey
2	distinctly phasey
3	objectionably phasey

(i) in listening room (ii) in free-field room

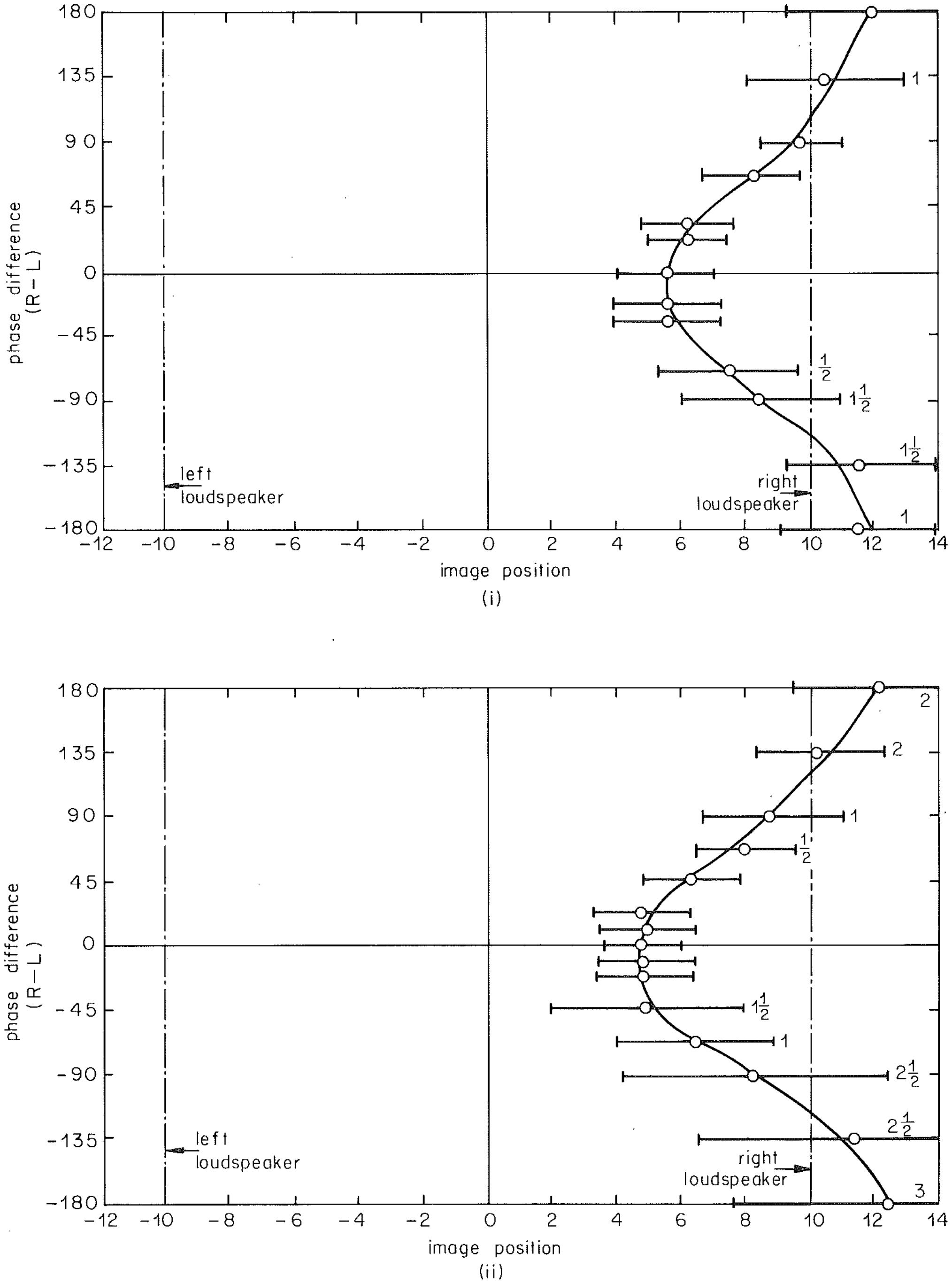


Fig. 7 - Image position versus interchannel phase-difference, for an interchannel level-difference of 8 dB

├───O───┤ N

Experimental result showing

image position .... O

image width .... ├──┤

and subjective disturbance factor .. N

N	Image Quality
0	not phasey
1	just detectably phasey
2	distinctly phasey
3	objectionably phasey

(i) in listening room (ii) in free-field room

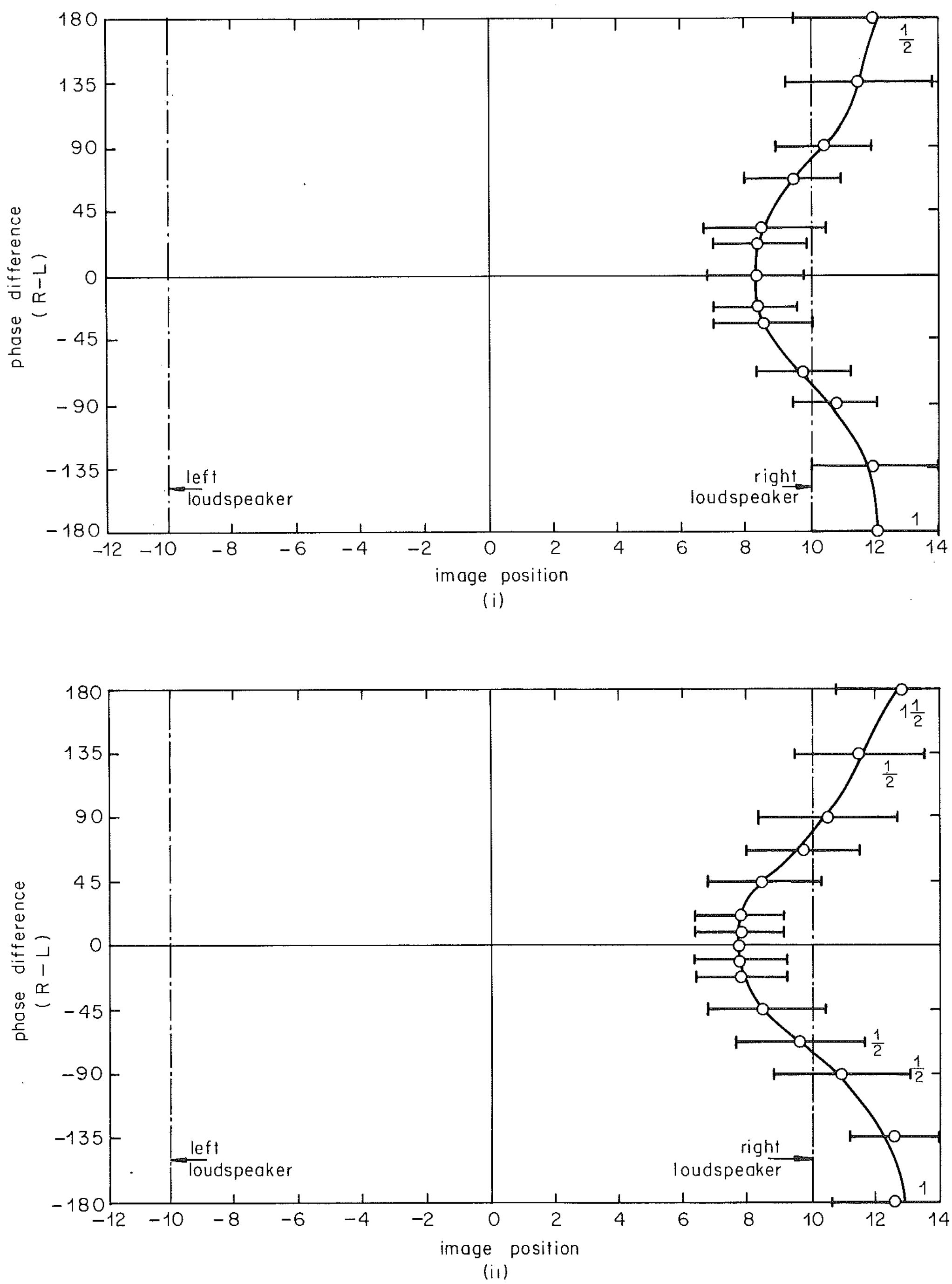


Fig. 8 - Image position versus interchannel phase-difference, for an interchannel level-difference of 14 dB

├———O———┤ N

Experimental result showing

image position .... O

image width .... ├——┤

and subjective disturbance factor .. N

N	Image Quality
0	not phasey
1	just detectably phasey
2	distinctly phasey
3	objectionably phasey

(i) in listening room (ii) in free-field room

Figs. 7 and 8 show the situation for level-differences of 8 dB and 14 dB, respectively. For the 8 dB case, the image shifts tend to be slightly smaller when the louder loudspeaker is lagging in phase, but the 14 dB results show complete antisymmetry with respect to phase-difference. In other words, the effect of a phase-difference is to displace any image towards the louder loudspeaker, regardless of whether it lags or leads in phase. Thus the Haas effect only applies to phase for small interchannel level-differences. This is shown very clearly in Figs. 9 and 10, in which the relationships between level-difference and image position are plotted. Fig. 9 shows that images shift consistently towards a phase-leading loudspeaker when this source is the louder of the stereo pair. Fig. 10, on the other hand shows the result when the quieter loudspeaker is phase-leading. For a level difference of 0 dB, central images are displaced towards the leading source: for a 4 dB difference, the off-centre images do not shift significantly: with images towards the edge of the stereo stage, corresponding to level-difference figures of 8 dB and 14 dB, the images are displaced towards the phase-lagging but louder loudspeaker.

5. Tolerances for stereo compatibility of quadraphonic encode matrices

Having discussed the phenomena at some length, it is important to give some specific information on the magnitude of phase-shifts which can be allowed in quadraphonic matrix systems, to ensure reasonable stereo compatibility. To this end, a set of encode matrix tolerances, based on the experimental results obtained in the listening room, has been derived. A scale of overall disturbance to any stereophonic image is specified, such that it incorporates both the phasiness and displacement parameters already considered. The five point scale is as follows:

1. Image is just perceptibly displaced from its 'true' (in phase) position, and is not perceptibly phasey in quality.

2. Image is noticeably displaced (corresponding to a position shift of greater than 1/10 but less than a quarter of the stereo stage width), and/or just perceptibly phasey.

3. Image is significantly displaced and/or noticeably phasey.

4. Image is radically displaced (shift greater than ¼ of stereo stage), and/or significantly phasey.

5. Image is unlocateable and/or objectionably phasey.

For the four interchannel level-differences investigated, the phase-differences causing these degrees of disturbance in the listening room are shown in Table 1. Thus, the restrictions on quadraphonic encode matrices, necessary to avoid disturbance to the stereo listener, can be readily found.

TABLE 1

Phase Tolerance Associated with Stated Degrees of Overall Image Disturbances Under Normal Listening Conditions*

Degree of Disturbance	Interchannel level-difference, D_L (dB)			
	0	4	8	14
1	±22°	+22°**	±34°	±45°
2	±45°	+45°**	±90°	±135°
3	±67°	(+90° (−45°	±135°	Never
4	±90°	+90°**	±135°	Never
5	±135°	(+180° (−135°	Never	Never

* Positive interchannel phase-differences correspond to the case of the louder loudspeaker leading.

** Negative phase shifts did not give consistent image displacements (see Figs. 6(i) and 6(ii)).

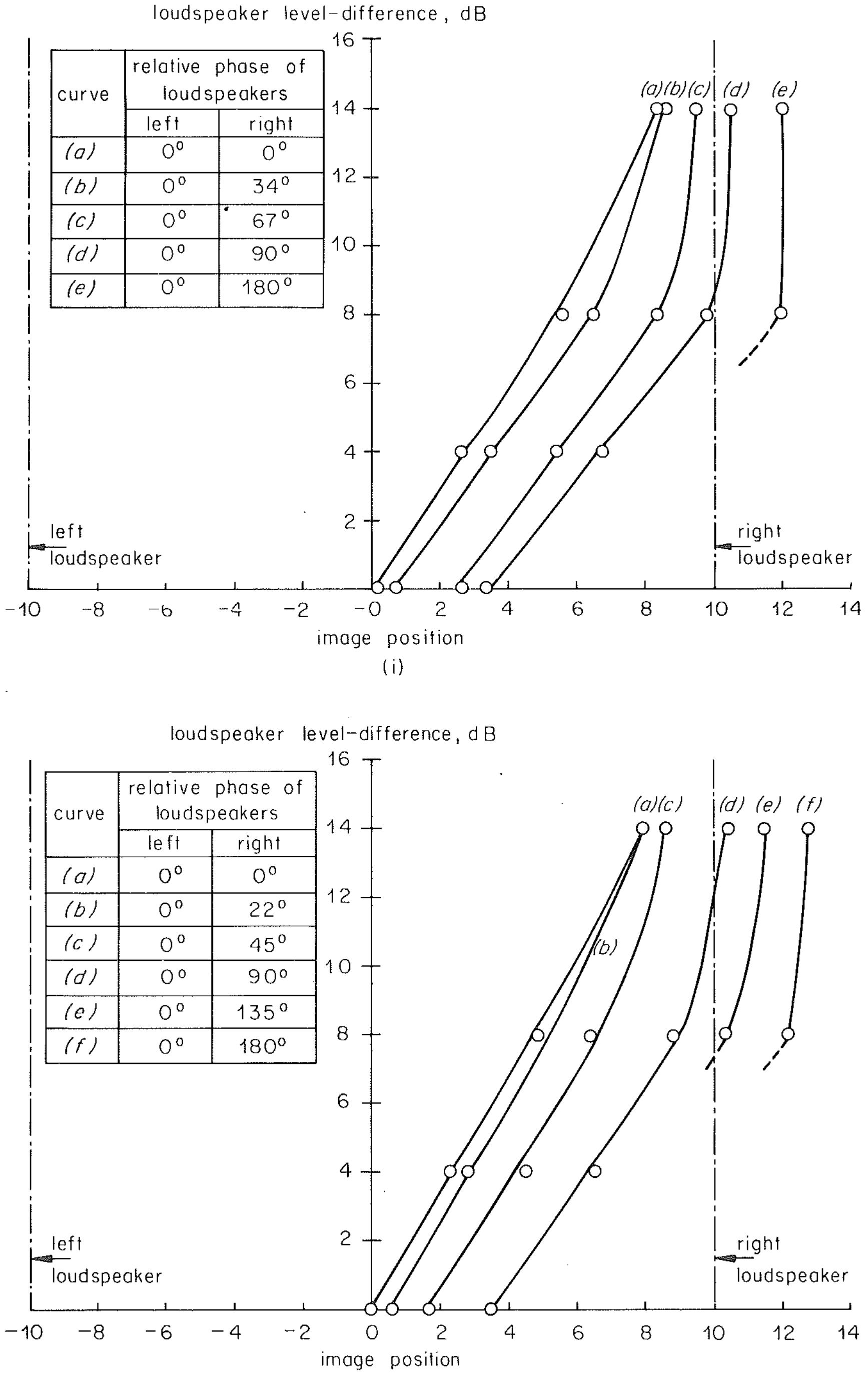
As stressed earlier, this work was done in the stereophonic mode only, using loudspeakers 60° apart. The information given in Table 1 therefore only strictly applies when considering the stereophonic presentation of matrixed material. However, phase-shifted cross-talk exists to a large extent in the quadraphonic presentation of matrixed material. Thus the information given is also relevant when considering subjective localisation effects in the four-channel mode. In fact, it is believed that subjective phase-phenomena tend to be exaggerated when using 90° loudspeaker spacings (as is usual for quadraphony). It is therefore probable that the subjective effect of interchannel phase-shifts in quadraphonic presentation may be quite severe, especially in the case of poorly designed matrices. However, it is possible that certain matrices, tailored in accordance with known properties of hearing can achieve subjectively acceptable results. Much has been written about this elsewhere.[7,8]

6. Conclusions

The effects of varying degrees of interchannel phase-difference on stereo programme material have been investigated by conducting a series of subjective tests in a free-field room and a listening room. The following results have been obtained:

1. Images formed by non co-phased signals are more subjectively disturbing in a free-field room than in a listening room. However, there is little difference in the displacements or spreads of the sound images in these two environments.

2. The effects of interchannel phase-difference tend to vary inversely with the interchannel level-difference.



(i)

curve	relative phase of loudspeakers	
	left	right
(a)	0°	0°
(b)	0°	34°
(c)	0°	67°
(d)	0°	90°
(e)	0°	180°

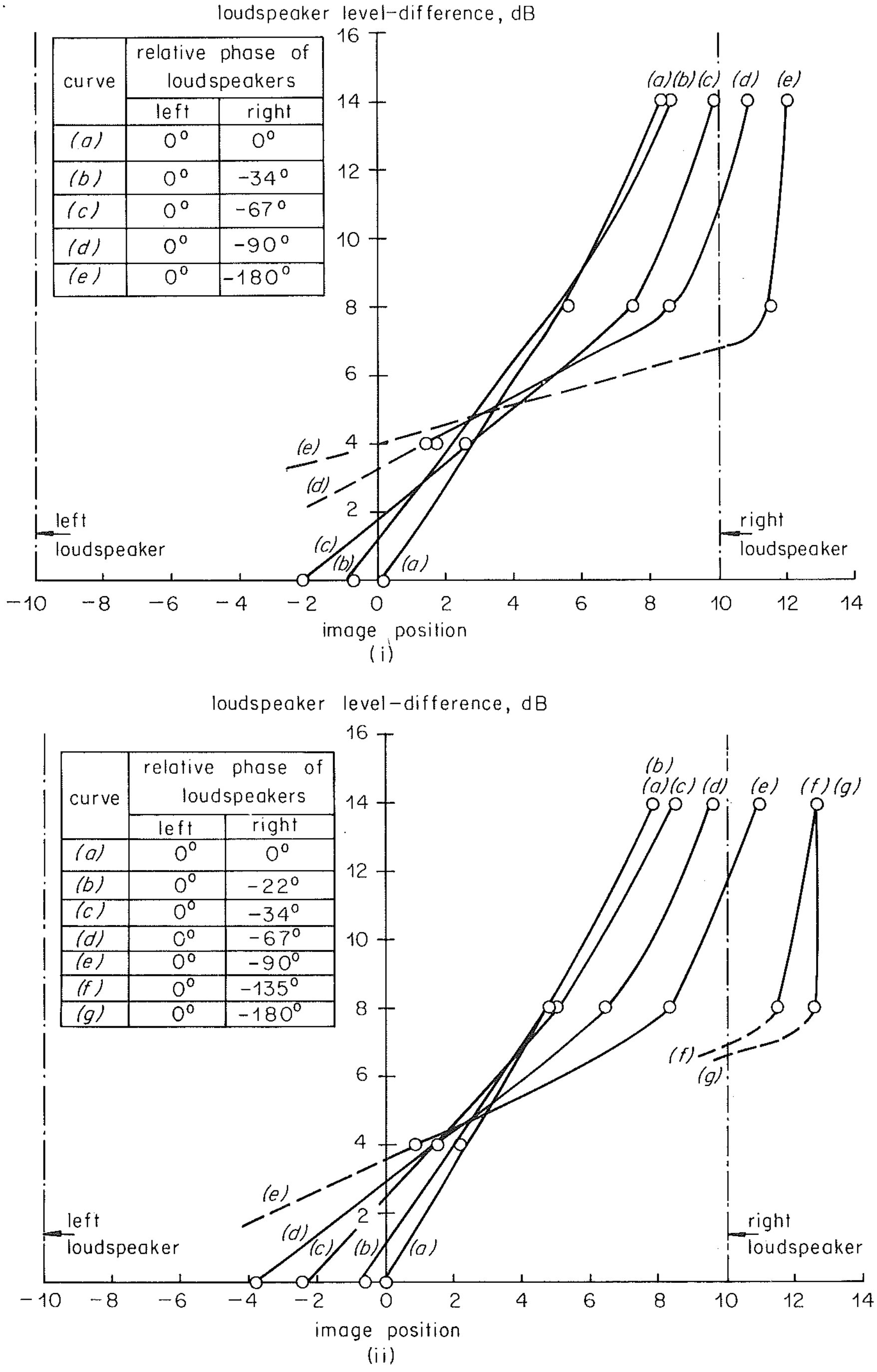
(ii)

curve	relative phase of loudspeakers	
	left	right
(a)	0°	0°
(b)	0°	22°
(c)	0°	45°
(d)	0°	90°
(e)	0°	135°
(f)	0°	180°

Fig. 9 - Image position versus interchannel level-difference, for selected interchannel phase-differences (with the louder loudspeaker leading in phase)

(i) in listening room

(ii) in free-field room



curve	relative phase of loudspeakers	
	left	right
(a)	0°	0°
(b)	0°	-34°
(c)	0°	-67°
(d)	0°	-90°
(e)	0°	-180°

curve	relative phase of loudspeakers	
	left	right
(a)	0°	0°
(b)	0°	-22°
(c)	0°	-34°
(d)	0°	-67°
(e)	0°	-90°
(f)	0°	-135°
(g)	0°	-180°

Fig. 10 - Image position versus interchannel level-difference, for selected interchannel phase-differences (with the louder loudspeaker lagging in phase)

(i) in listening room

(ii) in free-field room

Thus, central images are displaced and broadened to a greater extent than side images.

3. Interchannel phase-differences cause central images to be displaced towards the phase-leading loudspeaker. However, the effect on images at the side of the stereophonic stage is completely different. In this case, phase-differences invariably cause an image shift towards the louder loudspeaker.

4. A set of matrix tolerances, designed to ensure reasonable stereo compatibility for quadraphonic encoders, may be derived using data given in Table 1.

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Appendix I

Tables of Numerical Results

TABLE 2

Results for Interchannel Level Difference of 0 dB
(R Channel = −6 dB; L Channel = −6 dB)

Relative phase of speakers		LISTENING ROOM			FREE-FIELD ROOM		
L	R	Mean position of phase shifted image	Mean spread of image	Mean subjective degree of phasiness*	Mean position of phase shifted image	Mean spread of image	Mean subjective degree of phasiness*
0°	+180°	U**	U	3	U	U	3
0°	+135°	U	U	3	U	U	3
0°	+90°	+3·2	28°	1½	+3·5	35°	2½
0°	+67°	+2·6	20°	1	+2·7	28°	2
0°	+45°	–	–	–	+1·6	16°	1
0°	+34°	+0·7	16°	0	–	–	–
0°	+22°	+0·5	10°	0	+0·5	8°	½
0°	+11°	–	–	–	0	8°	0
0°	+6°	–	–	–	0	7°	0
0°	0°	+0·1	7°	0	0·0	8°	0
0°	−6°	–	–	–	0	9°	0
0°	−11°	–	–	–	−0·2	10°	0
0°	−22°	−0·5	9°	½	−0·6	10°	1
0°	−34°	−0·7	9°	0	–	–	–
0°	−45°	–	–	–	−2·5	19°	1½
0°	−67°	−2·2	22°	1½	−3·8	25°	2
0°	−90°	−2·2	32°	2½	U	U	3
0°	−135°	U	U	3	U	U	3
0°	−180°	U	U	3	U	U	3

* 0 = 'Not phasey'
1 = 'Just Noticeably phasey'
2 = 'Distinctly phasey'
3 = 'Objectionably phasey'

** U = Unlocateable

TABLE 3

Results for Interchannel Level Difference of 4 dB
(R = –4 dB; L = –8 dB)

Relative phase of speakers		LISTENING ROOM			FREE-FIELD ROOM		
L	R	Mean position of phase shifted image	Mean spread of image	Mean subjective degree of phasiness	Mean position of phase shifted image	Mean spread of image	Mean subjective degree of phasiness
0°	+180°	U	U	3	U	U	3
0°	+135°	+8·8	17°	2	U	U	3
0°	+90°	+6·8	13°	1	+6·5	35°	2
0°	+67°	+5·3	10°	½	+4·7	20°	1½
0°	+45°	–	–	–	+5·0	12°	1
0°	+34°	+3·5	12°	0	–	–	–
0°	+22°	+3·6	9°	0	+2·7	12°	½
0°	+11°	–	–	–	+2·2	8°	0
0°	+6°	–	–	–	+2·2	9°	0
0°	0°	+2·6	8°	0	+2·2	9°	0
0°	–6°	–	–	–	+2·2	10°	0
0°	–11°	–	–	–	+1·7	10°	0
0°	–22°	+1·9	7°	0	+1·4	8°	½
0°	–34°	+1·6	14°	½	–	–	–
0°	–45°	–	–	–	+1·4	13°	1½
0°	–67°	+2·6	25°	2	+1·4	34°	2½
0°	–90°	+1·4	36°	2	+0·8	40°	3
0°	–135°	U	U	3	U	U	3
0°	–180°	U	U	3	U	U	3

TABLE 4

Results for Interchannel Level Difference of 8 dB
(R = –4 dB; L = –12 dB)

Relative phase of speakers		LISTENING ROOM			FREE-FIELD ROOM		
L	R	Mean position of phase shifted image	Mean spread of image	Mean subjective degree of phasiness	Mean position of phase shifted image	Mean spread of image	Mean subjective degree of phasiness
0°	+180°	+12·0	10°	1	+12·2	12°	2
0°	+135°	+10·5	10°	1	+10·3	11°	2
0°	+90°	+9·8	6°	0	+8·8	13°	1
0°	+67°	+8·3	8°	0	+8·0	11°	½
0°	+45°	–	–	–	+6·3	12°	0
0°	+34°	+6·3	8°	0	–	–	–
0°	+22°	+6·3	7°	0	+4·8	8°	0
0°	+11°	–	–	–	+5·0	10°	0
0°	+6°	–	–	–	+4·8	7°	0
0°	0°	+5·6	8°	0	+4·8	8°	0
0°	–6°	–	–	–	+4·8	8°	0
0°	–11°	–	–	–	+4·8	9°	0
0°	–22°	+5·6	10°	0	+4·8	9°	0
0°	–34°	+5·6	10°	0	–	–	–
0°	–45°	–	–	–	+5·0	20°	1½
0°	–67°	+7·5	12°	½	+6·5	13°	1
0°	–90°	+8·5	13°	1½	+8·3	24°	2½
0°	–135°	+11·6	11°	1½	+11·5	30°	2½
0°	–180°	+11·5	12°	1	+12·5	28°	3

TABLE 5

Results for Interchannel Level Difference of 14 dB
(R = −2 dB; L = −16 dB)

Relative phase of speakers		LISTENING ROOM			FREE-FIELD ROOM		
L	R	Mean position of phase shifted image	Mean spread of image	Mean subjective degree of phasiness	Mean position of phase shifted image	Mean spread of image	Mean subjective degree of phasiness
0°	+180°	+12·0	8°	½	+12·8	10°	1½
0°	+135°	+11·5	9°	0	+11·5	8°	½
0°	+90°	+10·5	7°	0	+10·5	9°	0
0°	+67°	+9·5	7°	0	+9·8	7°	0
0°	+45°	–	–	–	+8·5	10°	0
0°	+34°	+8·5	9°	0	–	–	–
0°	+22°	+8·3	8°	0	+7·8	8°	0
0°	+11°	–	–	–	+7·8	8°	0
0°	+6°	–	–	–	+7·8	11°	0
0°	0°	+8·3	9°	0	+7·8	10°	0
0°	−6°	–	–	–	+7·8	9°	0
0°	−11°	–	–	–	+7·8	9°	0
0°	−22°	+8·3	7°	0	+7·8	8°	0
0°	−34°	+8·5	8°	0	–	–	–
0°	−45°	–	–	–	+8·5	9°	0
0°	−67°	+9·8	8°	0	+9·6	9°	½
0°	−90°	+10·8	7°	0	+11·0	10°	½
0°	−135°	+12·0	8°	0	+12·6	6°	0
0°	−180°	+12·0	8°	1	+12·6	10°	1

TABLE 6

Standard Deviations of Experimental Results (Averaged over all Phase Difference Levels)

In Listening Room

Interchannel level difference	Reference image position	Reference image spread	Phase shifted image position	Phase shifted image spread	Position shift between images
0 dB	0·5	5°	1·4	8°	1·4
4 dB	1·0	4°	1·5	6°	0·8
8 dB	1·0	2°	1·4	4°	1·2
14 dB	1·0	2°	1·2	1°	0·8
Mean	0·9	3°	1·3	5°	1·0

In Free-Field Room

0 dB	0·5	6°	0·8	10°	0·7
4 dB	1·0	4°	1·2	8°	0·6
8 dB	0·9	2°	1·5	5°	0·9
14 dB	1·3	2°	1·4	2°	0·4
Mean	0·9	4°	1·2	6°	0·7

Appendix II

Effects due to Limitations of Phase Shift Circuits

There are at present no circuit designs that will directly generate a phase shift of θ° (where θ is a constant, nominally independent of frequency). There are however, practical circuits which will generate a phase shift of $\phi + \theta$ (where ϕ is a function of frequency and θ, is nominally constant). Using such circuits, it is possible to produce two signals with a nearly constant phase difference. For instance, to generate a 90° phase difference, two circuits would be arranged to produce phase shifts of $\phi + \theta_1$ and $\phi + \theta_2$, where $\theta_1 - \theta_2 = 90^\circ$. There are two factors which it was thought might effect the audibility of the phase shifts produced in this way. One was the form of the variable ϕ, and the other was the inaccuracies in the value of θ.

The variable ϕ, depending on how it is generated, will be some combination of time delay and group delay. In this context, time delay can introduce no audible effect; and so only the effects of group delay needed to be investigated.

This was done very simply by switching a phase shift network (having $\phi \propto \log f$) in and out of a single audio channel, whilst monitoring the resultant signal via a high grade loudspeaker (type LD 5/5). This was done with a variety of test signals, and the results were played to several subjects in turn. None of these subjects were able to detect any significant difference between the direct and processed signals. It was therefore concluded that the group delay introduced by the type of network was of sufficiently small magnitude to be negligible.

The other factor which it was thought might effect test results was variations in the parameter θ. Fig. 11 shows a worst case example for a poorly adjusted three-pole phase-shift network, showing fluctuations of approximately ±10° about the nominal value of 90°. No quick check on the audibility of such fluctuations was found to be possible, and it was necessary to wait until a more accurate (±2°) four-pole network became available.

Fig. 12 shows the arrangement which was then used to compare:

i) a stereo image produced by equal amplitude signals with no phase difference between them.

ii) a stereo image produced by equal amplitude signals, but subject to the effects of an inaccurate 90° phase

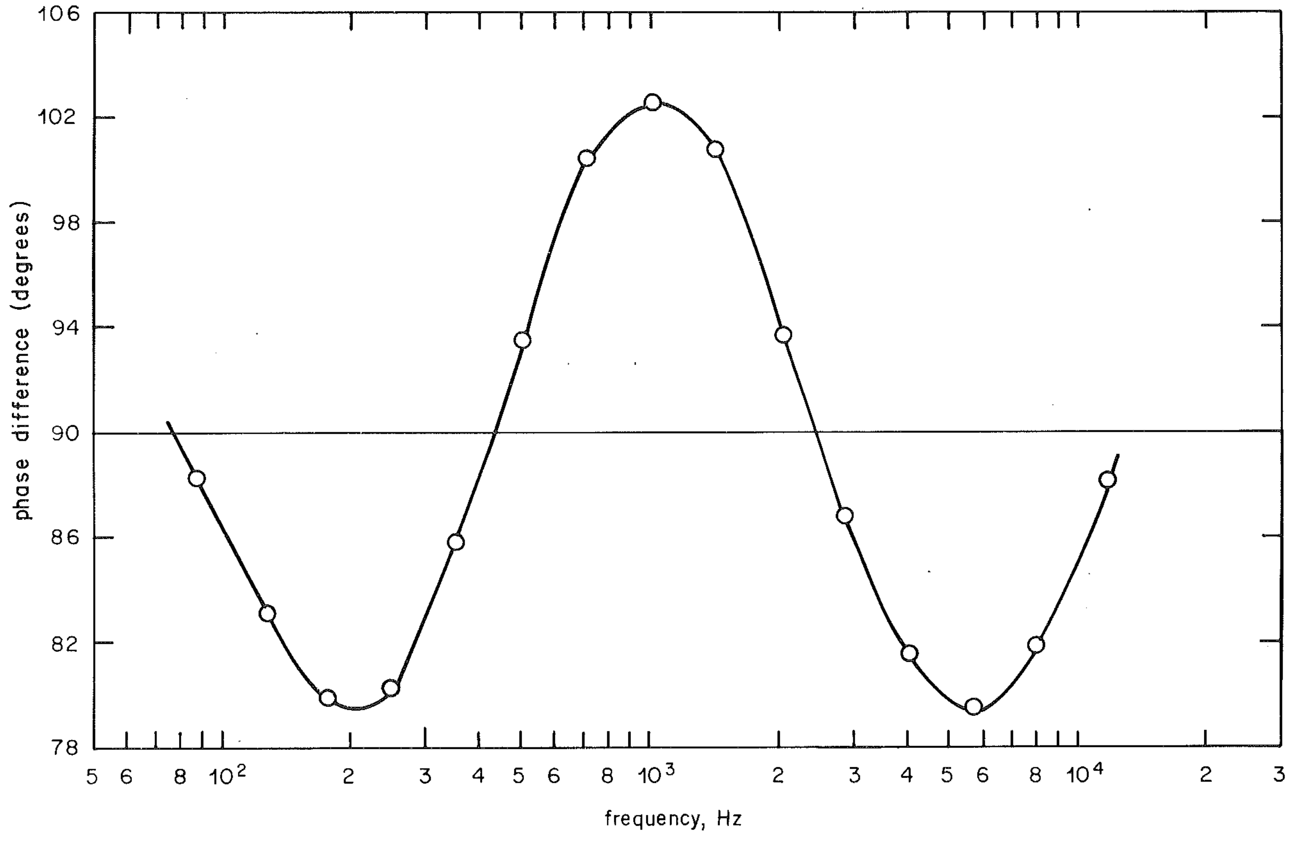

Fig. 11 - An example of phase-shift circuit inaccuracies

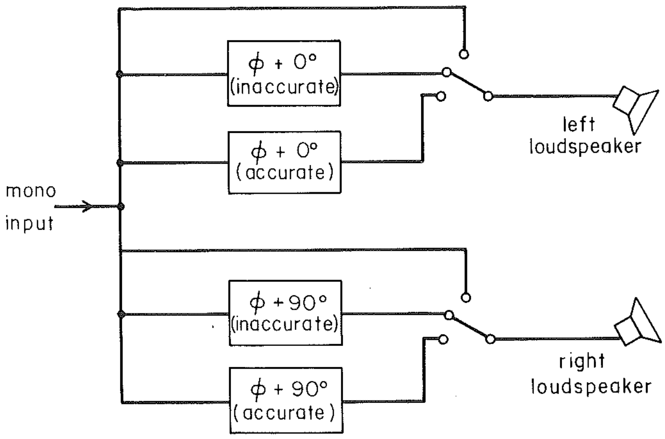

Fig. 12 - Comparison between accurate and inaccurate 90° phase shifts

difference between left and right channels.

iii) a stereo image produced by equal amplitude signals, but subject to the effect of an accurate 90° phase difference between left and right channels.

The comparisons were not conducted as a formal subjective test as the results proved to be so obvious: whilst there were just perceptible differences between conditions (i) and (iii) these were at least an order of magnitude smaller than the difference between (i) and (ii). It therefore seems reasonable to conclude that whilst inaccuracies in the 90° phase difference might produce just perceptible effects for the most discerning listener, such effects are negligible in comparison to those produced by the 90° phase difference itself. Thus it may be further concluded that in this context inaccuracies in the parameter θ, up to ±10°, are unlikely to be significant.

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